

NOISE REDUCTION USING
AN AIR-PERMEABLE CEILING

BY

WAYNE HARL BRADLEY

B.S., University of Illinois, 1991

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Electrical Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 1992

Urbana, Illinois

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ABSTRACT

A scaled (1 ft = 1 m) model of a German coffered ceiling [1] and three variations were designed, built, and tested at Construction Engineering Research Laboratory in Champaign, IL. To measure the efficiency of these ceilings, a scaled representation of the spectral range for small arms fire was radiated through the suspended models. The noise reduction measured for these models is compared to theoretical design curves calculated by Cremer in Beranek [2] for attenuation in lined ducts. When the ceilings are considered to be arrays of short lined ducts, Cremer's theory predicts the experimental noise reduction. Attenuation is found to be linearly dependent on the depth of the ceiling. In order to attenuate lower frequencies, the spacing between baffles must be increased. Therefore, size constraints will determine a lower bound on frequencies effectively attenuated by such ceilings.

ACKNOWLEDGEMENTS

The author would like to thank his advisors, Professor G. W. Swenson, Jr., and Professor P. D. Schomer, for their insight, guidance, and encouragement. The advice and assistance provided by the acoustics team and carpenter shop of USA-CERL are much appreciated. Most of all, the author would like to thank Tracy Neve, his future wife, for keeping him sane for the past four years.

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I. INTRODUCTION

Noise generated from the testing of and training with small arms on military installations is a serious problem. When residential areas surround these military posts, as is common in Europe, the military must take responsibility for solving the noise problem. This report describes a possible solution. It is an investigation of scaled models of sound absorbing ceilings for small arms ranges. These ceilings can attenuate the low frequency noise created by small arms before it becomes a problem for surrounding communities.

A full, solid ceiling spanning the entire testing range would provide the ideal solution for noise attenuation, but there are many reasons why such a ceiling would be impractical. Fresh air could not circulate throughout a range with a full, solid ceiling. This would lead to a congested, uncomfortable atmosphere within the range. Any additional weight on the roof, especially in areas where snow is common, would put a tremendous strain on the structure. Artificial lighting within the range would be very expensive. The lack of natural light from the sun would not allow the grass to grow within the range. Grass is a natural sound absorber and is commonly used in rifle ranges. It is clear that an open-to-the-air ceiling, which can effectively control noise, would be the ideal solution.

Dr. Buchta [1] designed a ceiling composed of a coffered or "egg-crate" arrangement of crisscrossed baffles as shown in Figure 1. The ceiling is actually a grid of short ducts designed to redirect and attenuate noise. It is currently being used in several small arms ranges including the one at Northeim, Germany. The top and side views of this range are shown in Figure 2. The depth and spacings between baffles measure about 1 m (some are slightly larger). Dr. Buchta performed extensive tests on this range and his results are discussed in Chapter III.

The Environmental Acoustics Team at the United States Army Construction Engineering Research Laboratory (CERL) in Champaign, Illinois, is interested in understanding and developing a semiempirical model for the ceiling structure designed by

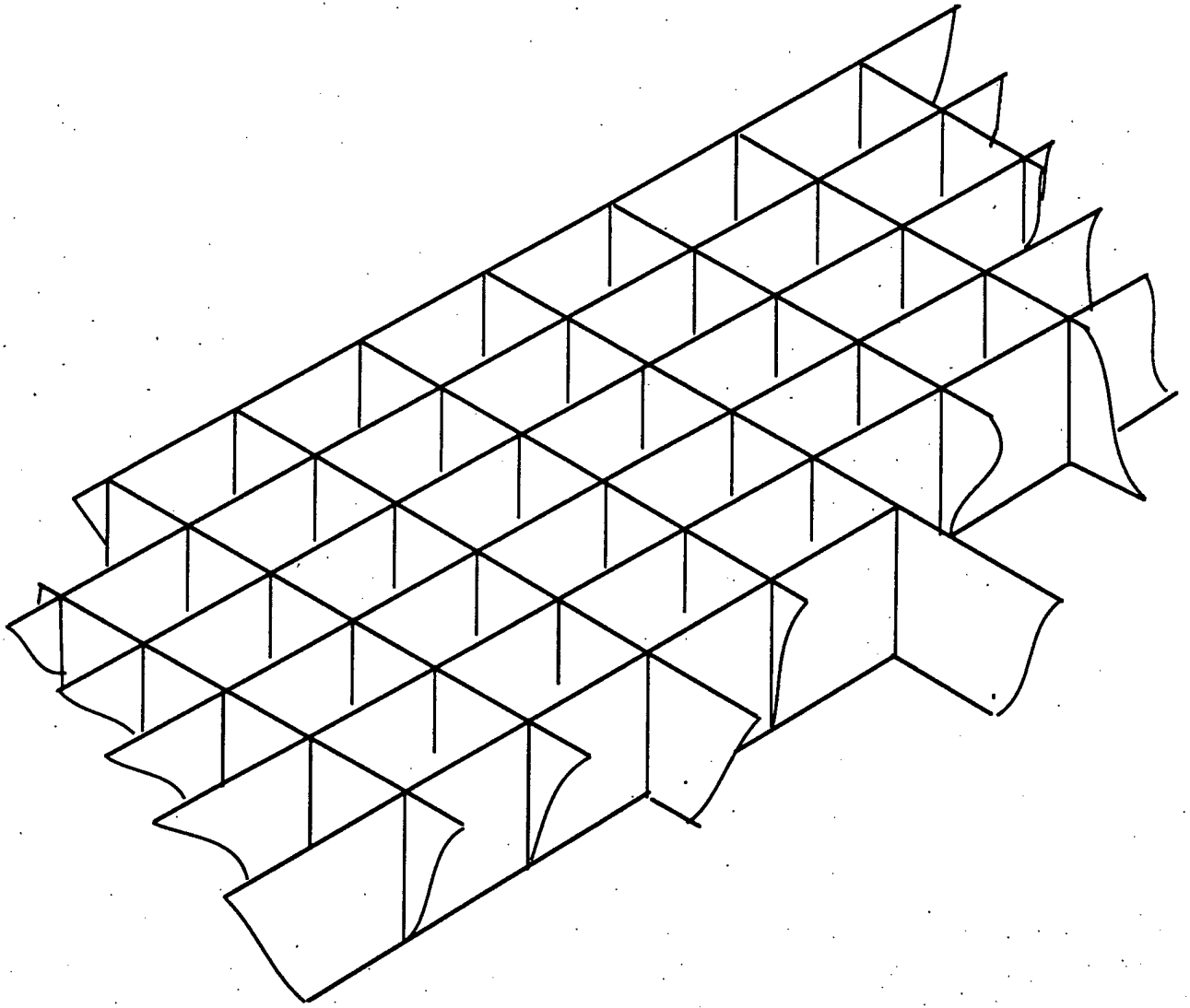


Figure 1. Isometric View of Buchta's Coffered Ceiling.

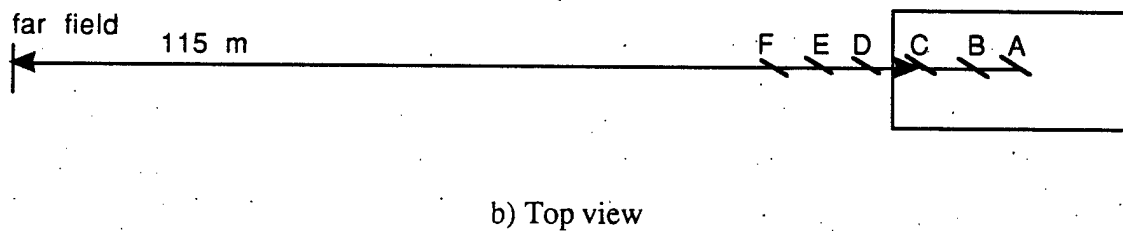
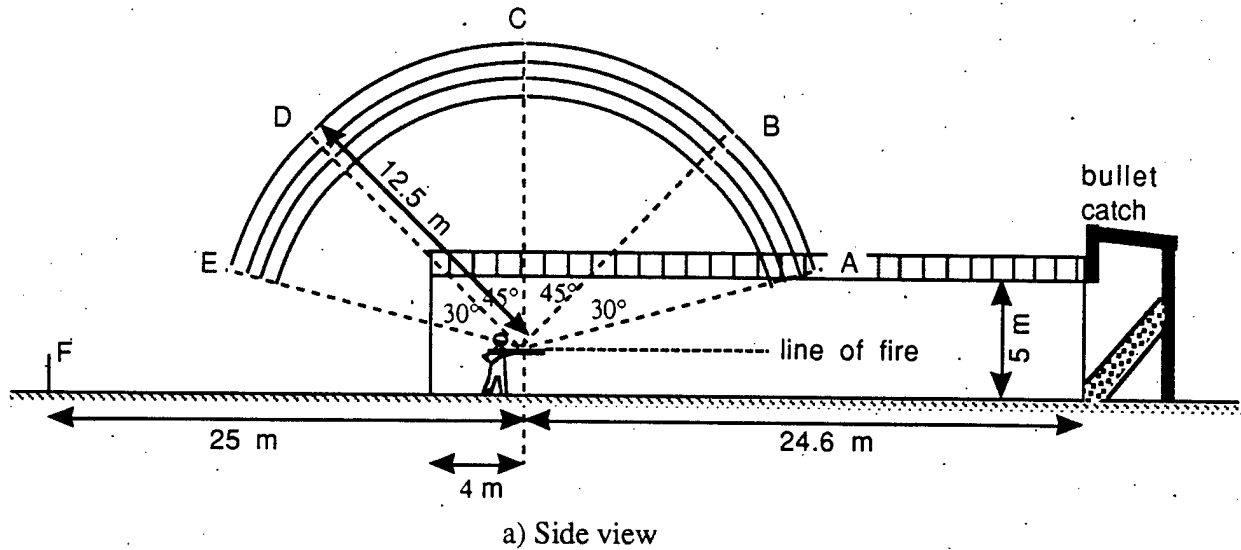


Figure 2. Northeim Rifle Range with Buchta's Coffered Ceiling. a) Side view of the range showing the near-field measurement locations A through F, b) Top view of the range at a smaller scale showing one of the far-field measurement locations.

Dr. Buchta. With this model, one could design for even greater overall attenuation, especially at low frequencies. Mr. Ken Eldred performed a preliminary analysis of the Buchta ceiling. In his analysis, Eldred [3] suggests that increasing the depth of the baffles would provide added attenuation for lower frequencies. This study analyzes the effect that baffle depth and baffle spacing have on attenuation.

Scaled (1 ft = 1 m) models were used at CERL to study the coffered ceiling design. Buchta's ceiling and three variations on his original model were designed, built, and tested in the course of this study. These variations included double depth (2 ft), double depth with altered path (described in Chapter IV.A), and double density (1/2 ft spacings).

To measure the efficiency of these ceilings, a scaled representation of the spectral range for small arms fire was radiated through the suspended models. The noise reduction measured for these models is compared to theoretical design curves calculated by Cremer in Beranek [2] for attenuation in lined ducts. When the ceilings are considered to be arrays of short lined ducts, Cremer's theory predicts the experimental noise reduction (Chapter V). Attenuation is found to be linearly dependent on the depth of the ceiling. In order to attenuate lower frequencies, the spacing between baffles must be increased. Therefore, size constraints will determine a lower bound on frequencies effectively attenuated by such ceilings. Comparisons were also made to Buchta's measurements in Chapter VI.A. Chapter VI.B discusses a two-stage ceiling, and Chapter VII concludes this thesis.

II. DEFINITIONS

The **intensity** of a sound wave is defined as the average rate of flow of energy through a unit area normal to the direction of propagation [4]. Typical units are W/m^2 , but it is customary to describe intensity levels through the use of **decibels** (dB) using the following formula:

$$10 \log_{10}(I/I_{\text{ref}}) \quad I_{\text{ref}} = 10^{-12} \text{ W/m}^2$$

Intensity measurement will be discussed in Chapter IV.C.

Insertion Loss is the difference in decibels between sound pressure levels measured at the same point in space, both before and after a ceiling is inserted between the measurement point and the noise source [5]. (This is the method used in the range testing at Northeim.)

Transmission Loss is the difference in decibels between the intensity incident on the ceiling and the intensity transmitted out from the ceiling [5]. (This is the measure used for current testing.)

Attenuation is the decrease of intensity between two points within a ceiling or duct not too near the ends [5]. It is typically measured in decibels per unit length. Total attenuation is the attenuation per unit length multiplied by the total length. The difference between attenuation and transmission loss is the **end effects**.

Noise reduction is used as a general term describing any of the above three measures.

Frequency will be given in hertz (Hz) and one-third octave bands. The relationship between the two is given by:

$$\text{frequency} = 10^{(0.1 * \text{one-third octave band})}$$

III. BACKGROUND

The concept of the coffered ceiling originated in Germany by Dr. Buchta. In 1984, Dr. Buchta, a consultant to the German Ministry of Defense, designed and tested what he described as *kassetten decken* at a rifle range in Northeim, Germany (Figure 2).

The range, without the ceiling, included large overhead beams which acted as bullet traps. Dr. Buchta used these to support his coffered ceiling. Since the beams could reflect the noise, he covered these, as well as the ceiling, with sound absorbing material.

Dr. Buchta's investigation was conducted in five stages. Initially, the noise from the firing of different guns was measured at set distances above and around the range before any ceiling baffles were put into place. This was stage zero. (The measurement locations can be seen on the side and top views in Figure 2.)

Stages one through four are shown in Figure 3: 1) Fourteen rows of vertical baffles 1 m deep and spaced 2 m apart served as the ceiling in stage one. These baffles were placed perpendicularly to the line of fire and consisted of 19 mm thick fiberboard covered on both sides by a 50 mm thick mineral wool with a density of 110 kg/m^3 . 2) In stage two, 15 additional rows were added to decrease the spacing to 1 m between the baffles. 3) In stage three, 14 rows of baffles 1 m apart were added parallel to the line of fire, forming a grid. 4) In stage four, the depth of every other cross-lane baffle was increased to 1.5 m.

Noise reduction of approximately 12 dB was measured in stages one and two for frequencies above 315 Hz. When the baffles in stage three were put into place, very little improvement was detected. The reason for this can be seen in Figure 2. Adding the baffles in stage three should have given improved noise reduction to the sides of the shooter, but since the measurement locations A through F were all directly above the line of fire, the noise reduction to the sides of the shooter was not measured. In stage four, the increased depth of some of the baffles provided an additional 2 to 3 dB of noise reduction.

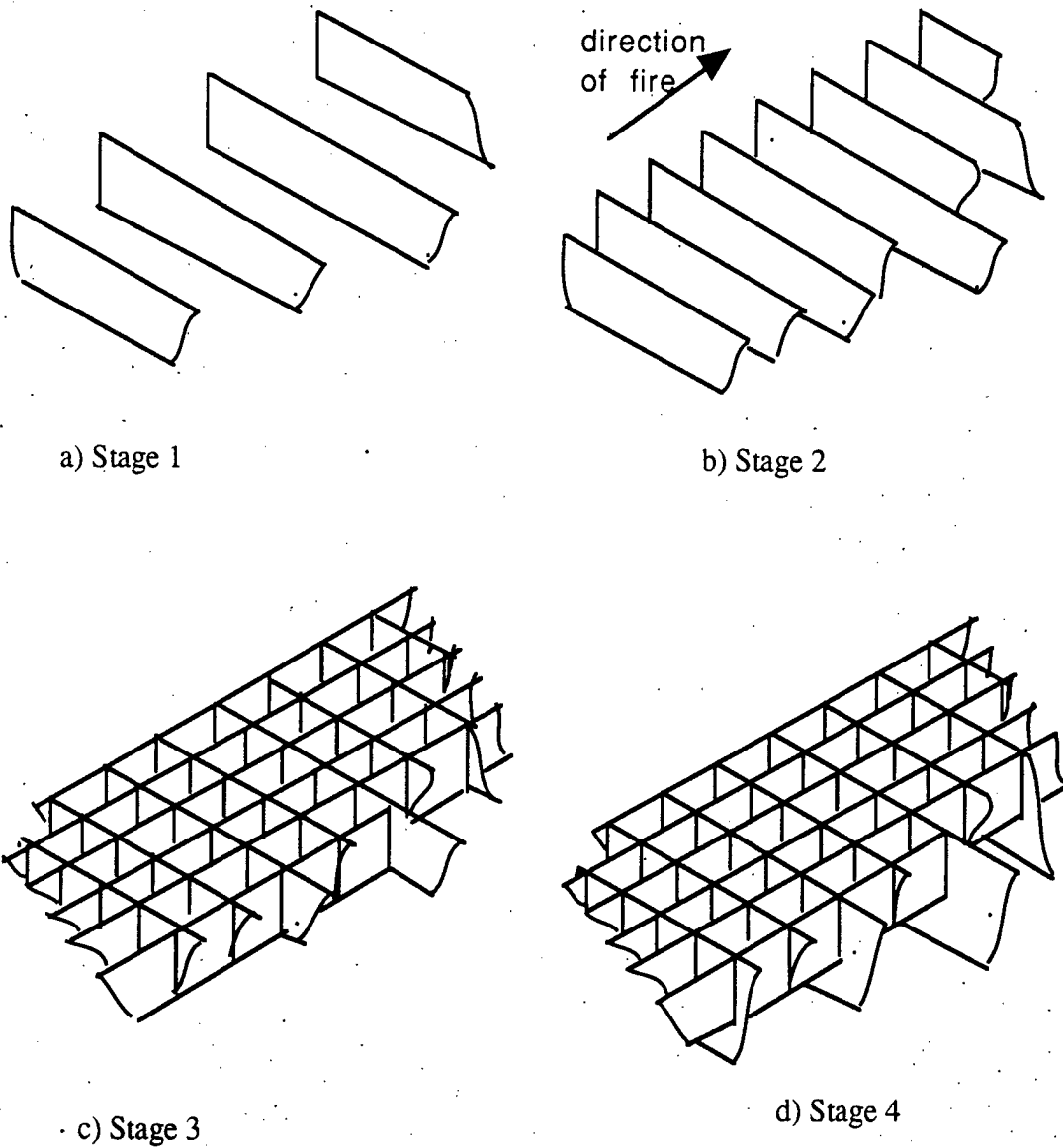


Figure 3. German Testing. a) Stage 1 consists of 14 rows of vertical baffles 1 m deep and 2 m apart. b) In stage 2, 15 additional rows of vertical baffles 1 m deep are added in to give a spacing of 1 m. c) Stage 3 shows the addition of 14 rows parallel to direction of fire. d) In stage 4, the original 14 baffles are lengthened to 1.5 m.

The results of the study in Northeim, Germany, were so encouraging that a permanent stage-three type of ceiling was installed in a range at Veitshoheim, Germany. Measurements above and around this range show a 12 to 14 dB reduction, which is consistent with Northeim testing.

IV. DESIGN

A. Ceiling Models

In order to develop a model for Buchta's ceiling system, scaled models of his stage three (the Veitshoheim version) and three variations of it were designed, built, and tested at CERL. The scaling is 1 m equals 1 ft, or approximately one-third scale. This was selected because of the availability of the acoustic ceiling tile which was used to line the sides of the chambers. As will be discussed in the next section, ceiling tiles that provide the desired attenuation come in a 1 ft by 1 ft by $\frac{3}{4}$ in size.

The size of the ceilings could not be more than 20 ft by 20 ft, due to space limitations. A model size of 16 ft by 16 ft was selected. This allowed for 2 ft of overhang in each corner to provide connection to a support frame and overhead crane. This connection can be seen in the photograph in Figure 4. The support frame and its placement between the crane and ceiling are seen in Figure 5 and the photographs in Figure 6. The support frame, built of 2x4 lumber, is used to counteract the compression force caused by the angled support cables. In addition, since the cables connected directly to the ceiling are vertical, the area above the corners of the ceiling is free from interference and can be tested.

The first ceiling constructed was a scaled model of Buchta's stage three. The ceiling's baffle cores are made of 1x12 lumber with $\frac{1}{2}$ in finishing strips, which results in a 1 ft depth and provides sufficient strength for the ceiling to support itself. Unfortunately, the $\frac{3}{4}$ in thickness is greater than the one-third scale desired. The outer frame is made from 4, 20 ft long 2x12 lumber (16 ft plus two 2 ft overhangs). Thirteen baffle cores spaced $12\frac{3}{4}$ in (12 in for the length and $\frac{3}{4}$ in for the thickness of the ceiling tiles) apart are screwed into this outer frame. Short baffle cores bridge the original 13 to form a grid containing 196 chambers. Figure 7 shows a side, top, and corner view of ceiling #1 along with a photograph taken from below the structure.

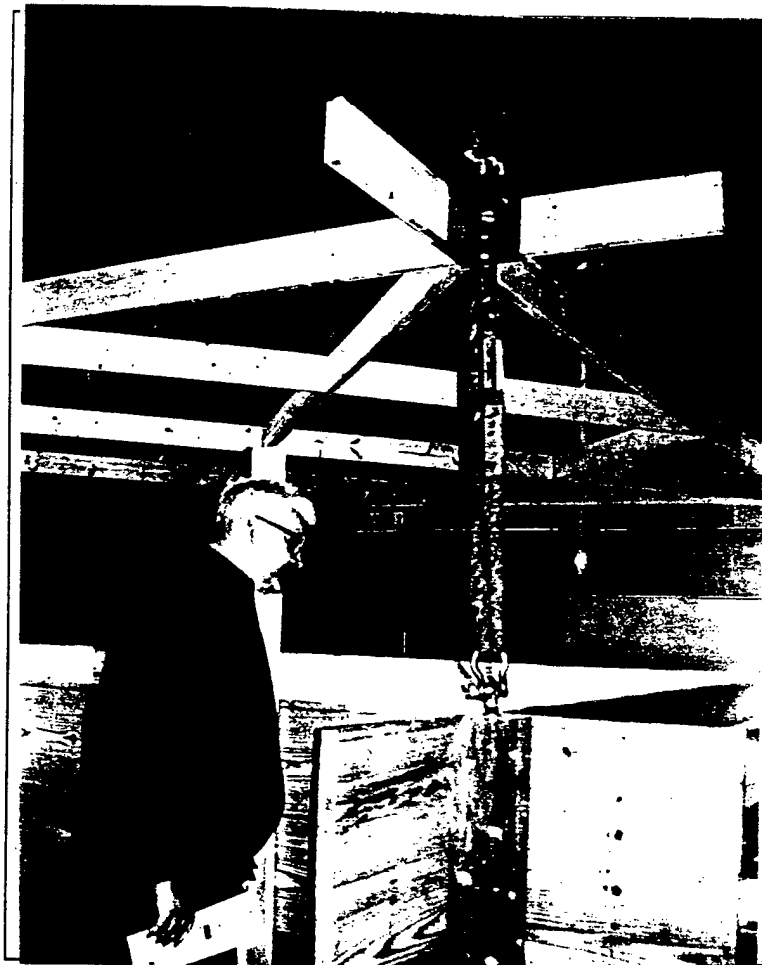


Figure 4. Connection to Support Frame and Ceiling.

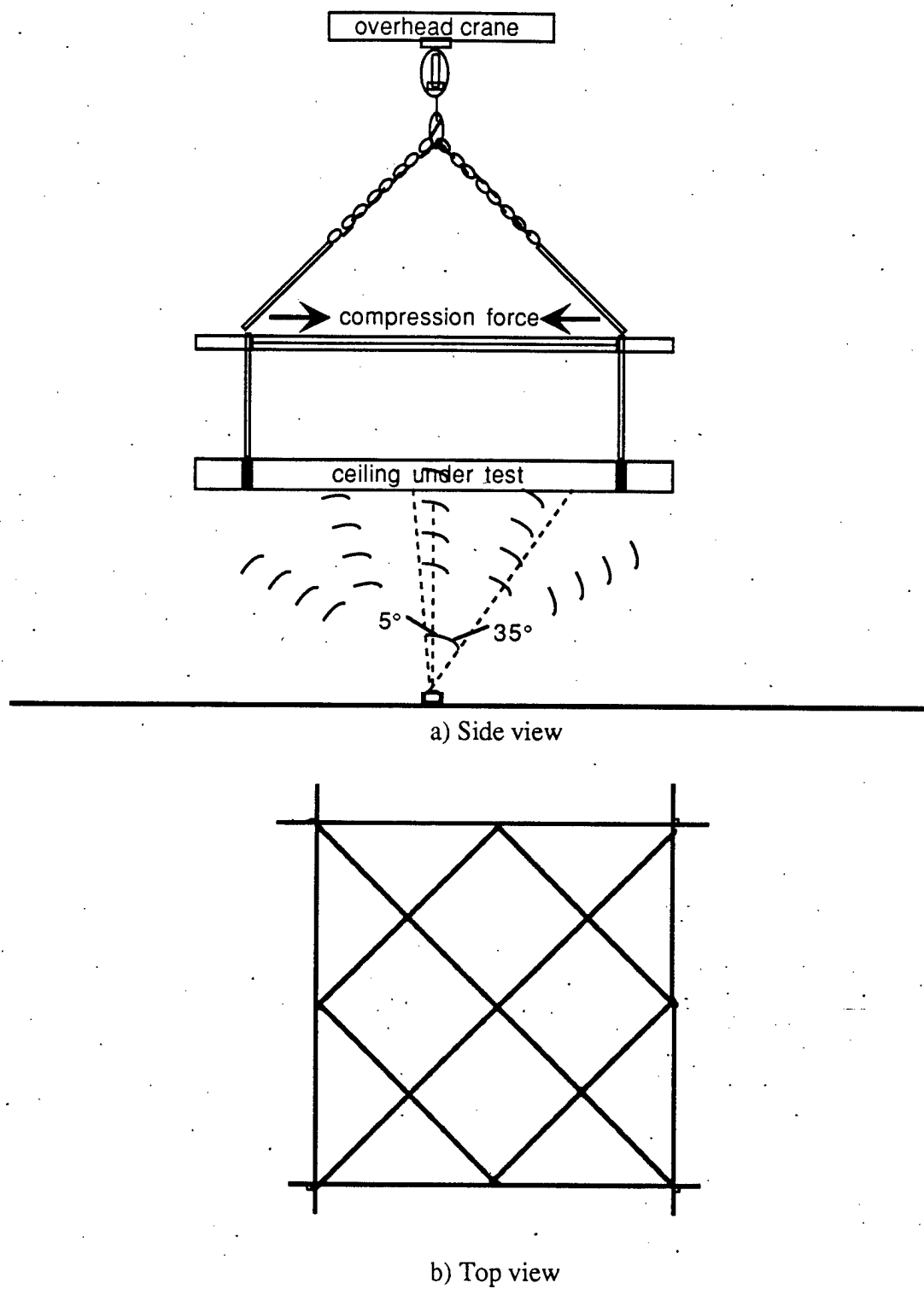
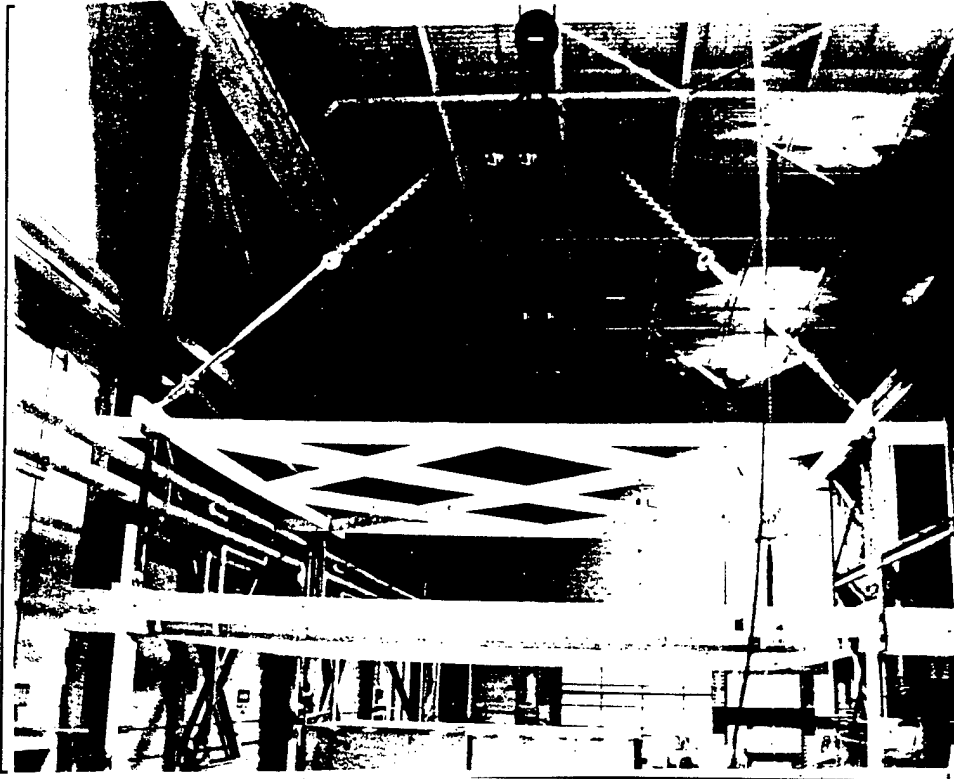


Figure 5. Support Frame. a) Side view. b) Top view.

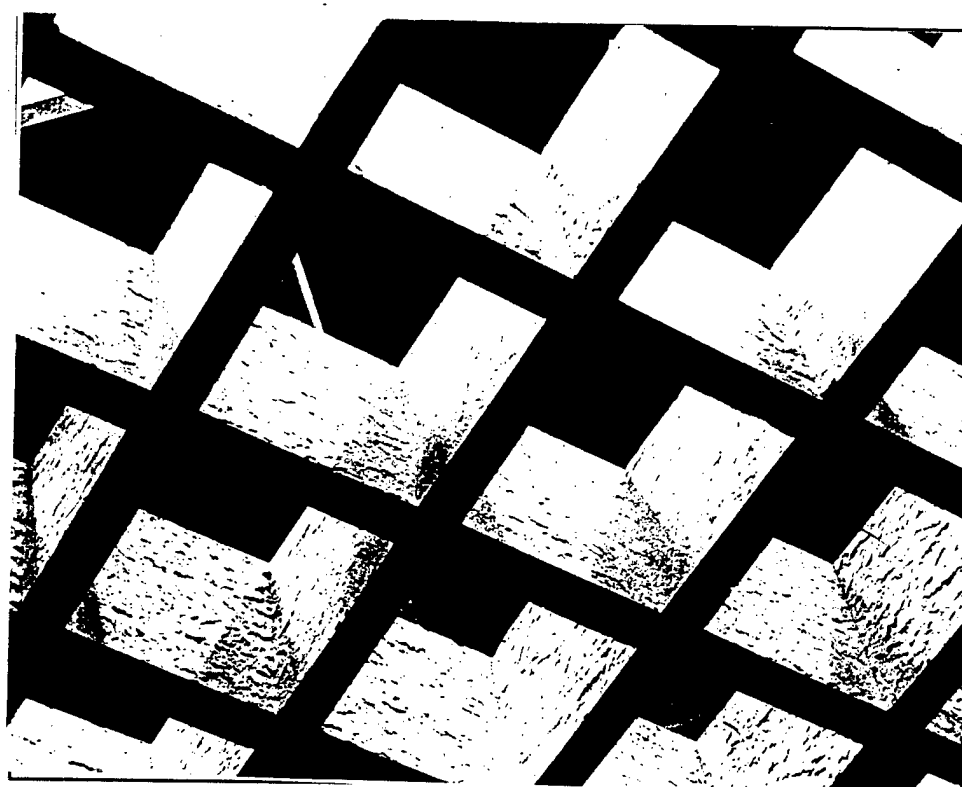
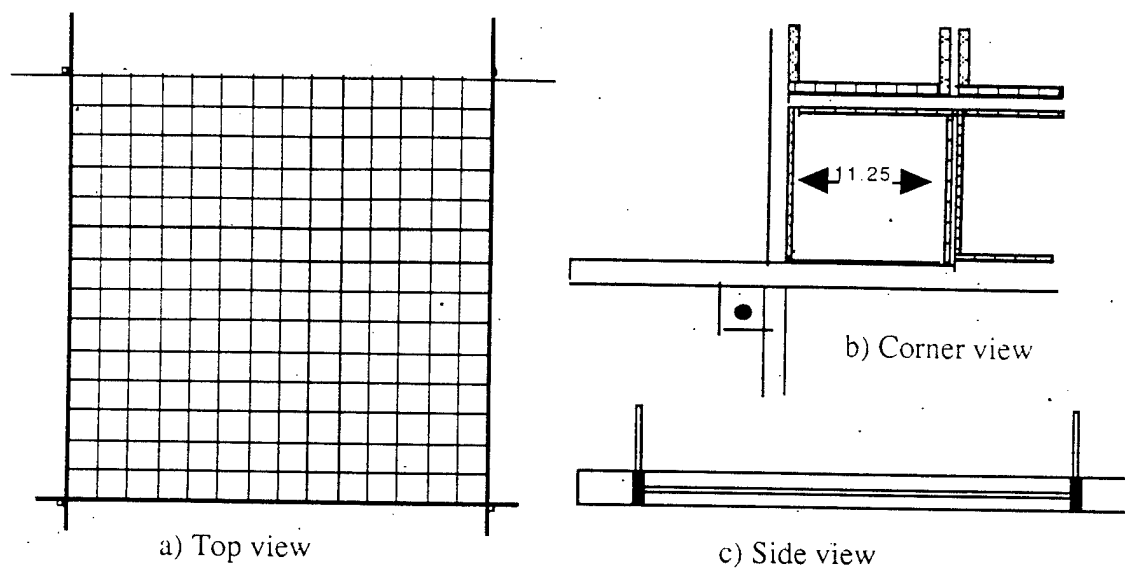


a) Side view



b) Height

Figure 6. Ceiling under Test. a) Side view. b) Height.



d) Bottom view

Figure 7. Ceiling #1. a) Top view showing 196 chambers. b) Corner view showing the open air dimension and tile placement. c) Side view of 1 ft depth. d) Photo taken from underneath.

Acoustic ceiling tiles are glued to all four walls of each chamber. The specific ceiling tile used in all ceiling models is USG *Acoustone*, "F" *Fissured*. The absorption coefficients are given in Table 1. The bulk density of the tile is 320 kg/m^3 , and, as previously stated, the dimensions of each tile are 3/4 in by 12 in by 12 in. Thus, the free flow area in each chamber as shown in Figure 7c) is 11 1/4 in by 11 1/4 in, and the depth is 12 in.

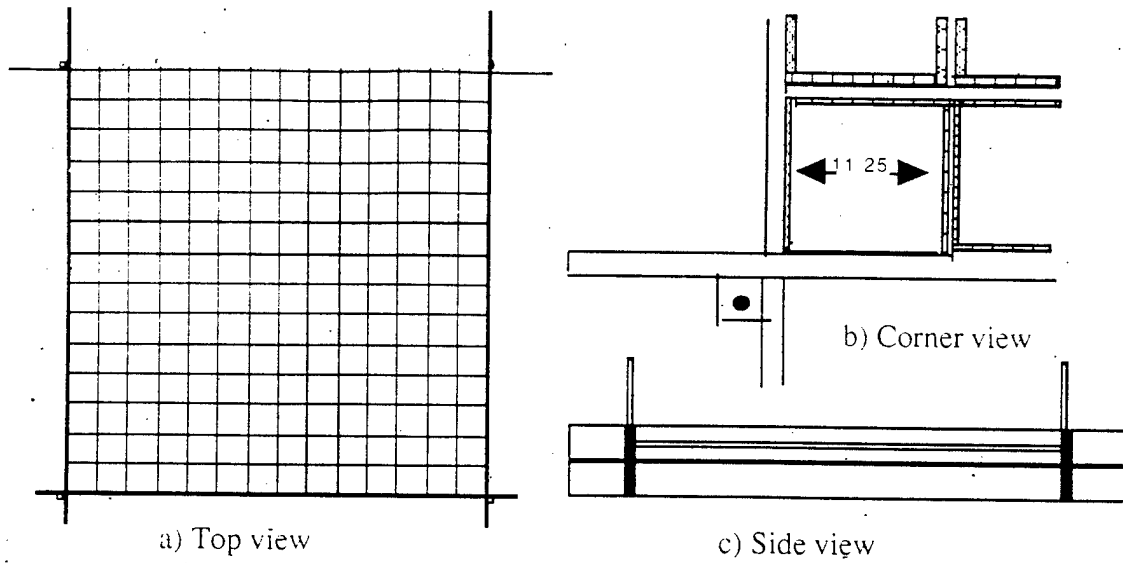
Table 1. Absorption Coefficients: Band Center Frequency (Hz)

<u>125</u>	<u>250</u>	<u>500</u>	<u>1000</u>	<u>2000</u>	<u>4000</u>
0.05	0.23	0.71	0.97	0.86	0.93

Ceilings #2, #3, and #4 are variations on the design developed for test ceiling #1. To increase attenuation, the depth of test ceiling #2 is twice that of test ceiling #1. This change should increase the vertical directivity of the sound radiating through the ceiling, thus increasing the attenuation in the horizontal direction, while providing direct attenuation [2]. To scale ceiling #2 a replica of ceiling #1 was constructed. The two were joined together, doubling the depth. As seen in Figure 8, all of the other dimensions remain unchanged.

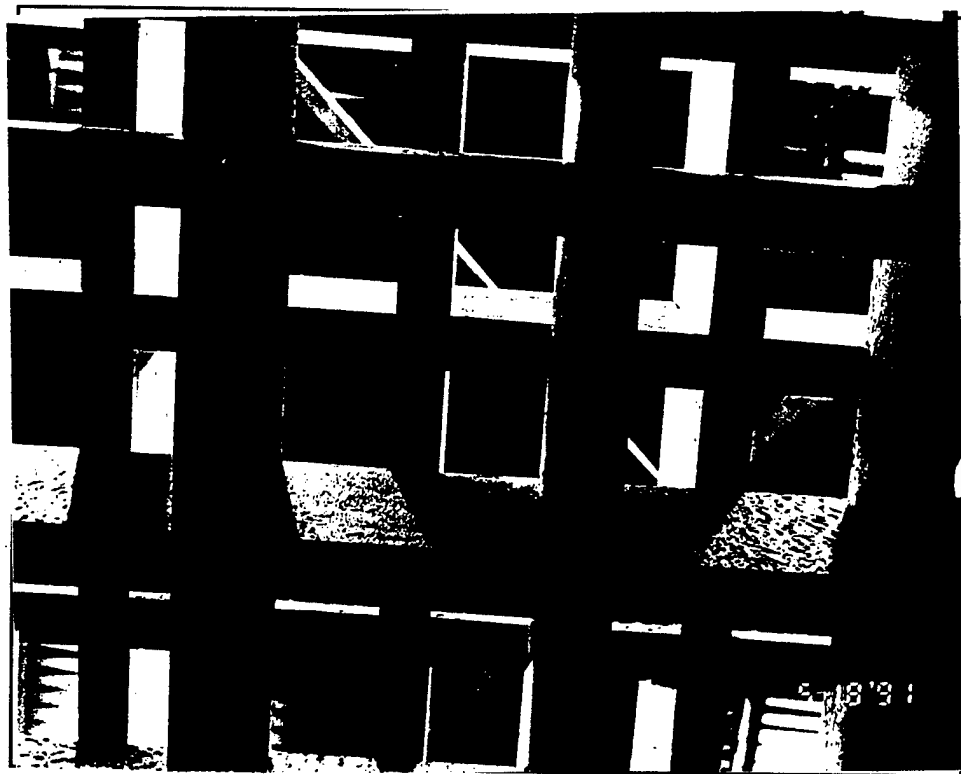
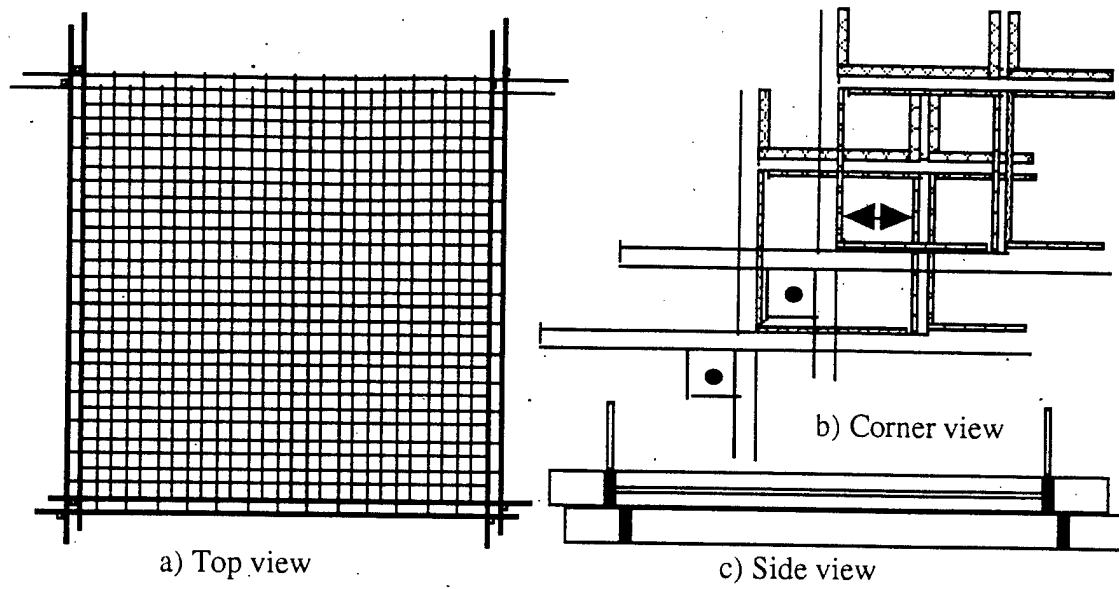
Ceiling #1 and its replica are used for test 3. The difference between test ceilings #3 and #2 is that when the two ceilings are joined in test ceiling #3, they are "staggered". This is shown in the top and corner views in Figure 9. The open-air chamber centers of the top ceiling are directly above intersections of baffle cores in the bottom ceiling.

For test ceiling #4, the open air spacing is approximately halved. It shrinks from 11 1/4 in by 11 1/4 in to 4 1/2 in by 4 1/2 in. This is accomplished by using ceiling #1 and building inserts to divide each chamber into four smaller chambers. This is shown in Figure 10. The photograph in Figure 10d) shows the top of the ceiling with some of the inserts removed so that they can be better understood.



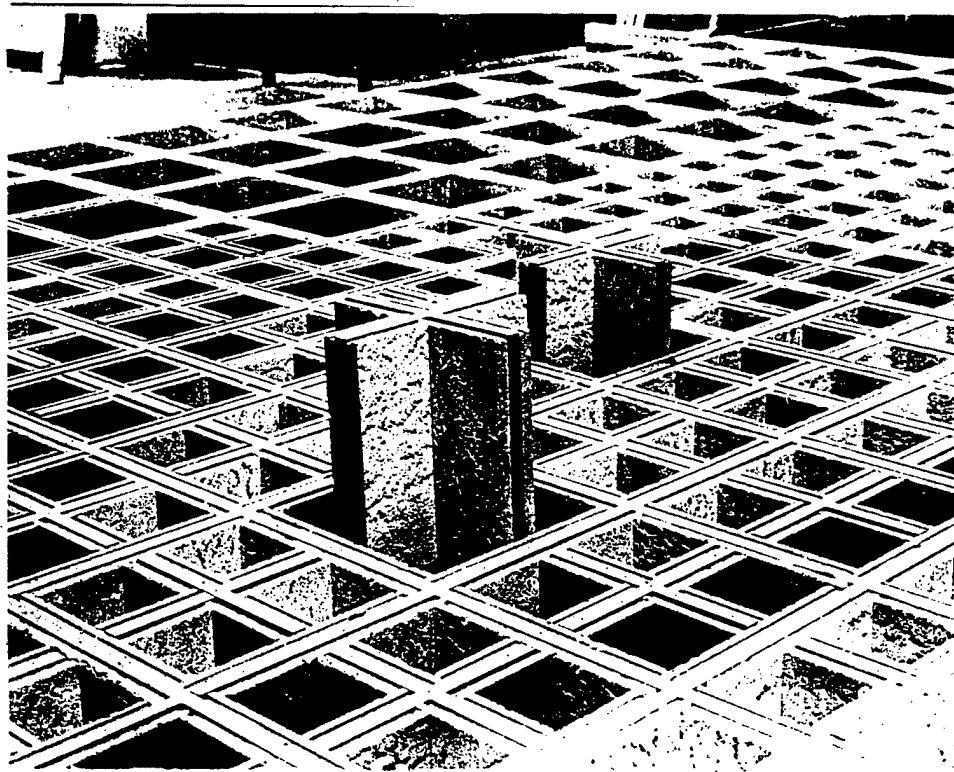
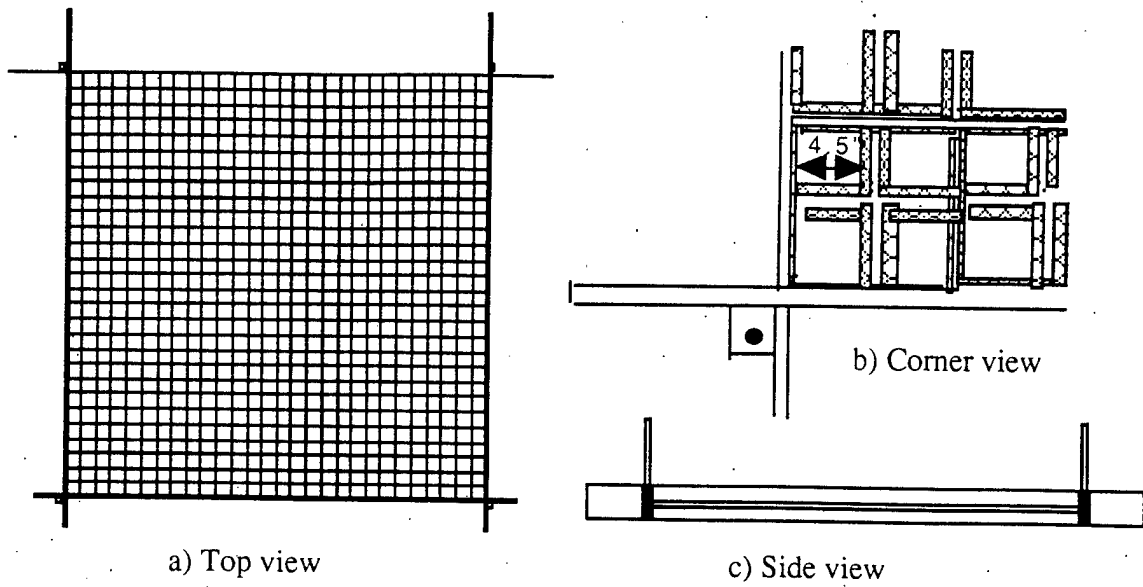
d) Bottom view

Figure 8. Ceiling #2. a) Top view showing 196 chambers. b) Corner view showing the open air dimension and tile placement. c) Side view of 2 ft depth, d) Photo taken from underneath.



d) Bottom view

Figure 9. Ceiling #3. a) Top view showing 196 chambers staggered above another 196 chambers. b) Corner view showing the staggering close up. c) Side view of 2 ft depth. d) Photo taken from underneath.



d) Top view

Figure 10. Ceiling #4. a) Top view showing 784 chambers, b) Corner view showing the open air dimension and tile placement. c) Side view of 1 ft depth. d) Photo taken from above showing removed and missing inserts.

B. Source

The source for the testing at CERL is a scaled representation of the spectral range for small arm fire. The sound exposure spectrum level from the rear of an M-16 is shown in Figure 11. More than 75 percent of the energy is in the range from 125 Hz to 1250 Hz (band 21 to 31). Since the scale is 1 m equals 1 ft, the frequency is shifted up by approximately five, one-third octave bands.

$$\log_2\left(\frac{1\text{m}}{1\text{ft}} * \frac{39\text{in}}{1\text{m}}\right) = 1.7 \approx \frac{5}{3}$$

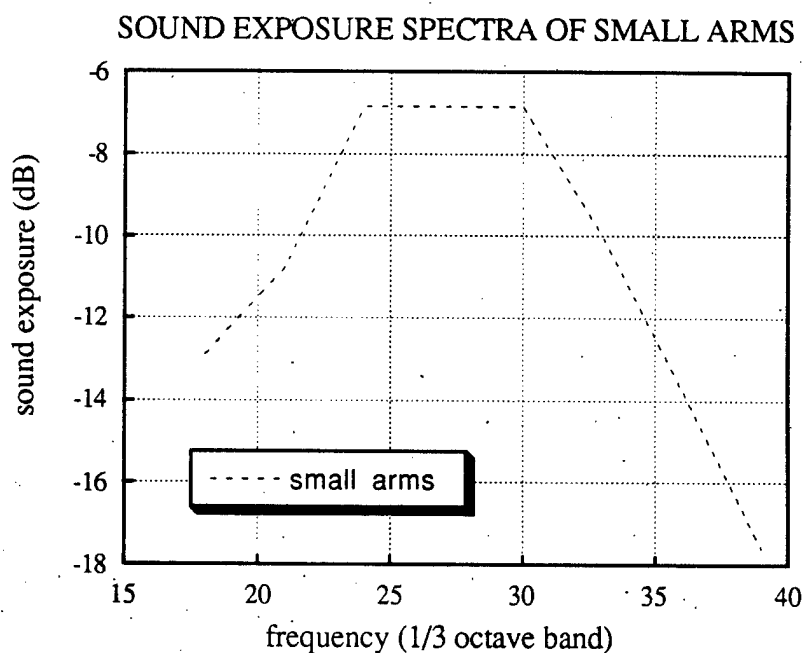


Figure 11. Small Arms SEL Spectra Behind the Shooter.

The frequencies of 125 Hz to 1250 Hz (band 21 to 31) are scaled to 400 Hz to 4 kHz (band 26 to 36).

As shown in Figure 12, the test source sound is generated by a white noise generator, one-third octave band filter set, amplifier, and Celestion speaker. The white

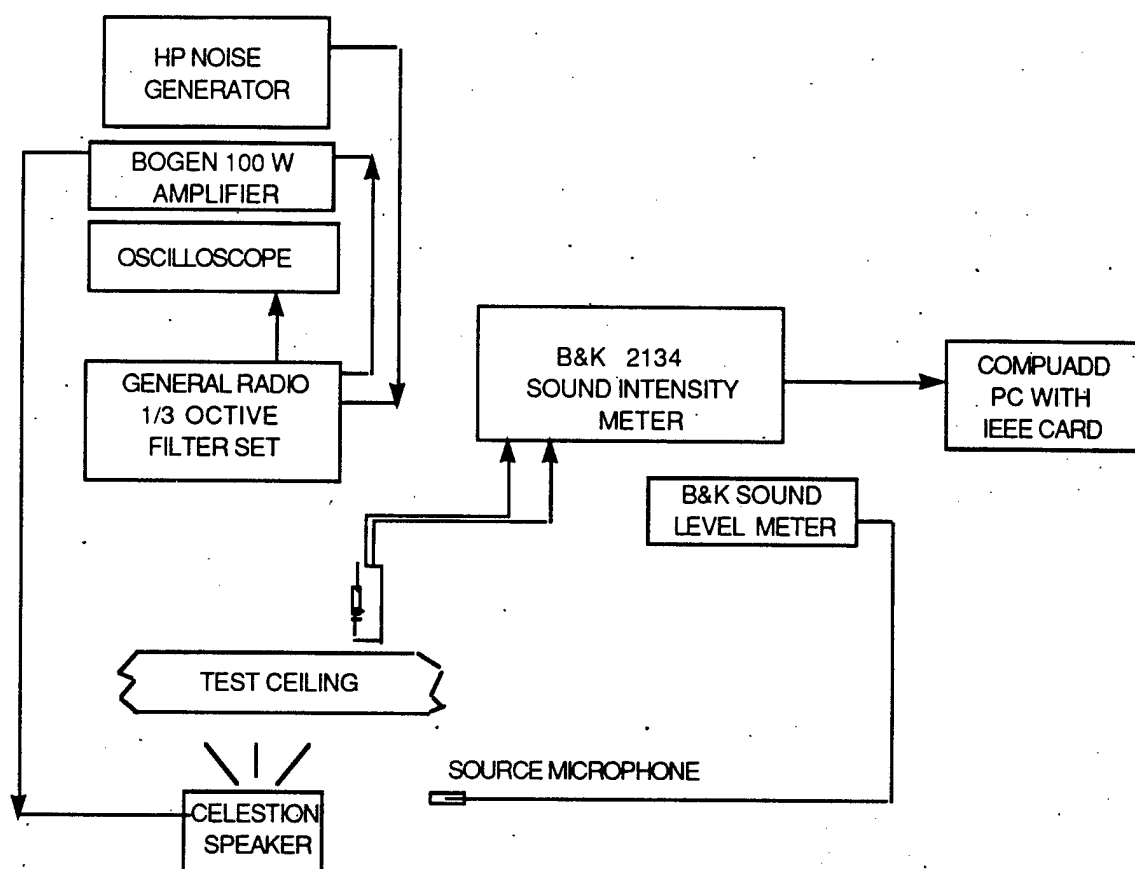


Figure 12. Test Equipment.

noise is filtered to give equal energy sound, or pink noise, per each 1/3-octave band in the range from 400 Hz to 4 kHz.

To provide constant output from the speaker, a source microphone connected to a sound level meter is positioned 2 ft above and 2 ft to the side of the speaker. During the test, the level was checked for consistency.

C. Intensity Measurement

Sound intensity was measured with a B&K 2134 sound intensity meter. Intensity is the product of acoustic pressure and particle velocity. To implement this product [4], the meter uses a two-microphone probe as shown in Figure 13a). The pressures at microphones A and B are denoted as p_a and p_b . The acoustic pressure is taken as the mean pressure:

$$\text{acoustic pressure} = \frac{(p_a + p_b)}{2}$$

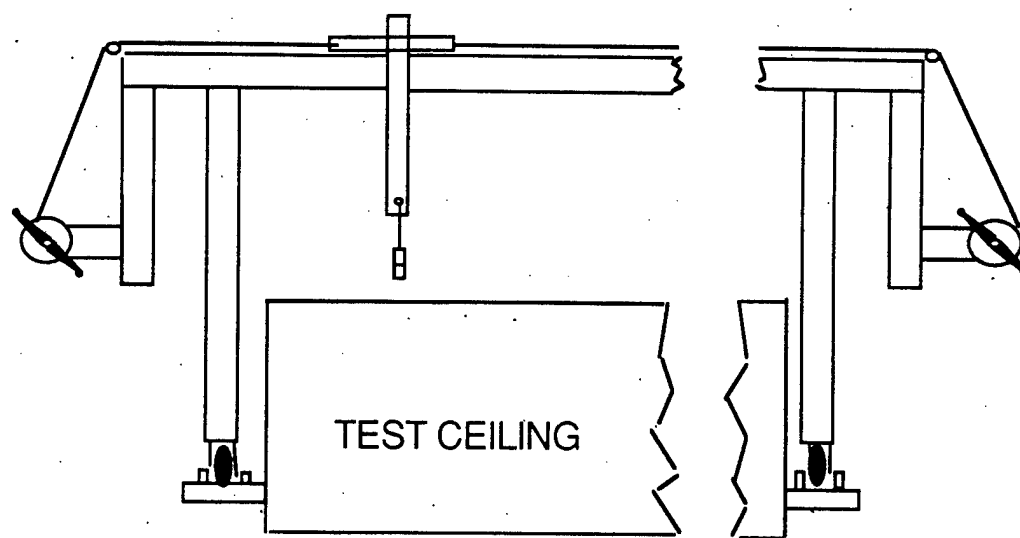
Direct measurement of particle velocity requires devices such as hot wire anemometers.

The two-microphone technique uses an approximation based on Euler's relationship:

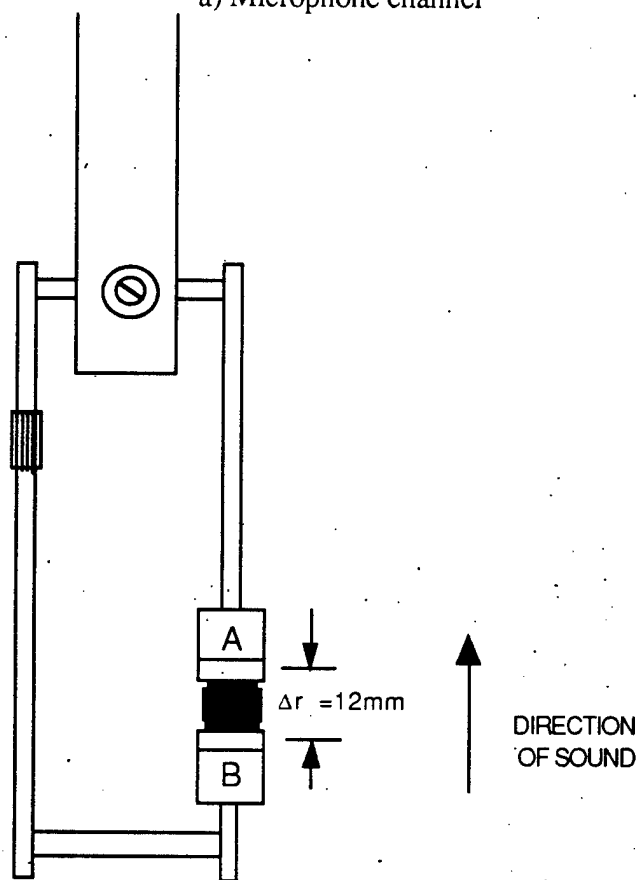
$$\rho \frac{\delta u}{\delta t} = - \text{grad } p,$$

where ρ is the density of air, $\text{grad } p$ is the pressure gradient, and u is the particle velocity vector. In one direction, ρ thus becomes

$$\rho \frac{\delta u_r}{\delta t} = - \frac{\delta p}{\delta r}$$



a) Microphone channel



b) Probe

Figure 13. Sound Intensity Measurement. a) Microphone channel. b) Probe.

which gives the integral relationship:

$$u_r = -\frac{1}{\rho} \int \frac{\delta p}{\delta r} dt$$

If the spacing Δr between microphones A and B, is small compared to a wavelength, the formula becomes approximately:

$$u_r = -\frac{1}{\rho \Delta r} \int (p_b - p_a) \delta t$$

Therefore, the intensity is approximated by

$$I = \frac{-(p_a + p_b) \int (p_a - p_b) dt}{2\rho_0 \Delta r}$$

In this study, the highest frequency (shortest wavelength) of interest was 4 kHz, so the approximation is valid since Δr is 12 mm and the wavelength of a 4 kHz wave is 86 mm.

The intensity meter performs the calculation for each one-third octave band. In this study, these data were transmitted to a personal computer using the IEEE protocol card. Software in the PC wrote these data into a file for storage and later use.

D. Probe Cart and Track

In this study the intensity above the ceilings was measured. Since the ceilings span 16 ft, a method to reach every location above the ceilings had to be devised.

The intensity probe (Figure 13a)) can be made to move above any chamber of a ceiling with the aid of the channel in Figure 13b). Figure 14 is a photograph of the probe channel and operator. The probe is attached to a block of wood which rides within the



Figure 14. Intensity Probe and Operator.

channel. A wooden arm, balanced by a lead weight, suspends the probe approximately 1 in above the surface of the ceiling. The block of wood is connected on both sides, with fishing line, to reels so that the cart can move the length of the channel. The entire system is on wheels which run along wooden tracks on the side of the ceiling. This enables movement perpendicular to the length of the track.

When the ceiling is hoisted 8 ft above the ground, scaffolds are built on the sides of the ceiling with reels so that both the channel and cart can be accessed and manipulated. The intensity above a chamber is taken as the energy average of three evenly spaced 4-sec scans across one length of the chamber. Because the size of the scan for ceiling #4 was so small, only one shorter scan was made. Therefore, the equipment operator must communicate to the two channel operators the scan to be made on a particular chamber.

Before testing the ceilings, it was necessary to measure the intensity that would be incident upon them. As a control, all equipment and supporting structures were put into place, and the intensity of the speaker at a plane 8 ft above the ground was measured.

V. RESULTS

The coffered ceiling structure can be thought of as a grid of short lined ducts. Sabine's theory of attenuation in lined ducts (Munjal [6]) is useful for wavelengths much larger than the duct width. For the ceilings and frequencies of interest in this study, the duct width is on the order of a wavelength. Cremer (Beranek [2]) has written a design procedure which may be used in this case. In his theory, Cremer assumes that sound will propagate only as plane waves in the fundamental mode.

A simplification of Cremer's theory for the attenuation in rigid ducts that are lined on two sides with a porous material is given by Ingard in Beranek [5]. Figure 15 shows five design curves for open areas of 17 percent to 80 percent. Open area is the ratio of the area within the lining to the area including the lining.

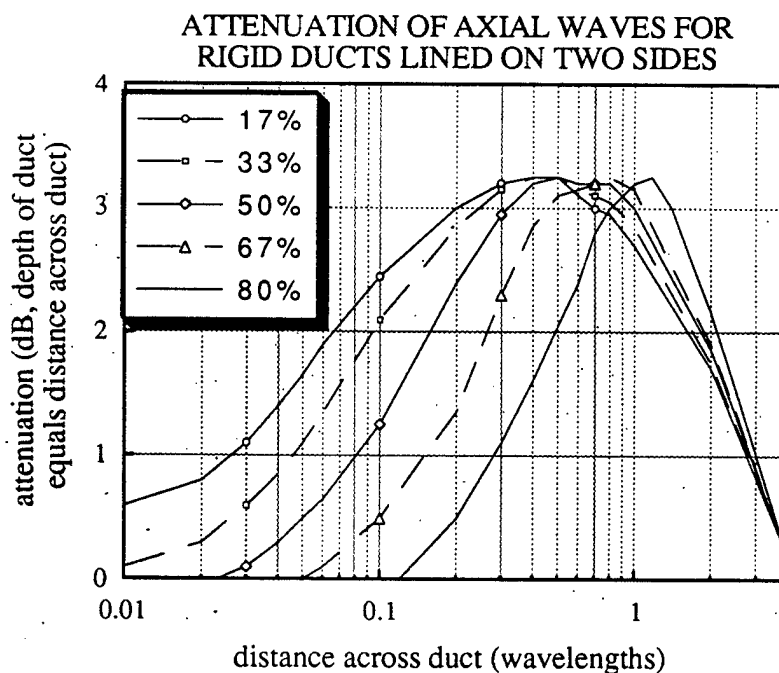


Figure 15. Attenuation of Axial Waves for Rigid Ducts Lined on Two Sides with a Porous Material. To find the attenuation for a duct lined on four sides multiply by two [5].

To apply the design curves to the study conducted at CERL, several issues have to be addressed. First, the chambers of the ceiling will be thought of as ducts. The attenuation for our case, where all four walls of each chamber are lined with a porous material, is double that given by the curves for ducts lined on two walls [5]. Attenuation in decibels is given for a duct length (chamber depth) equal to duct width (chamber spacings). For larger chamber depths, the attenuation is scaled up by the ratio of depth to spacing. The data taken at CERL are transmission losses which consists of attenuation plus end effects. Since the ceiling is 8 ft from the source, it can be assumed that the radiated noise is nearly planar when it reaches the ceiling. End effects caused by the change in area upon entering and leaving a duct are quite small in the case of plane waves [5]. Thus the term noise reduction will be used generically to describe attenuation and transmission loss.

The grid facilitates the gathering of data as a function of angle of incidence. In this study, two angles of incidence were studied, 5 degrees and 35 degrees, as shown in Figure 2. The 5-degree location encompasses the four center chambers of the ceilings. This is very close to normal incidence for which the design curves are intended.

Figure 16 shows the noise reduction for ceiling #1 at 5 degrees as a dotted line and at 35 degrees as a dashed line. The open area is $(11.25 \text{ in} / 12.75 \text{ in})^2 = 0.78 \approx 80$ percent. The theoretical curve for 80 percent (Figure 15) is scaled and plotted as a solid line in Figure 16.

Cremer's theory predicts the noise reduction for the data taken at 5 degrees. The largest deviations occur at 3.2 kHz and 4 kHz (band 35 and 36). These deviations are due to the higher modes of propagation. In his article, *Design Curves for Circular and Annular Duct Silencers* [7], Ramakrishnan and Watson discuss the reason. Since the frequency scale is fine at higher frequencies, the number of modes will increase over a shorter range. The design curves in Figure 15 take into account only the fundamental mode.

The measured noise reduction at 35 degrees follows the theoretical curve up to 1 kHz (band 30) where the duct width is nearly one wavelength. At higher frequencies, the measured noise reduction is greater than the noise reduction predicted for normal incidence. When a duct is wide when compared with a wavelength, the open area presented to an obliquely incident wave is reduced significantly. Thus, the duct length relative to the presented duct width is greater giving a greater attenuation. Conversely, when the duct is narrow compared to a wavelength, the angle of incidence is irrelevant.

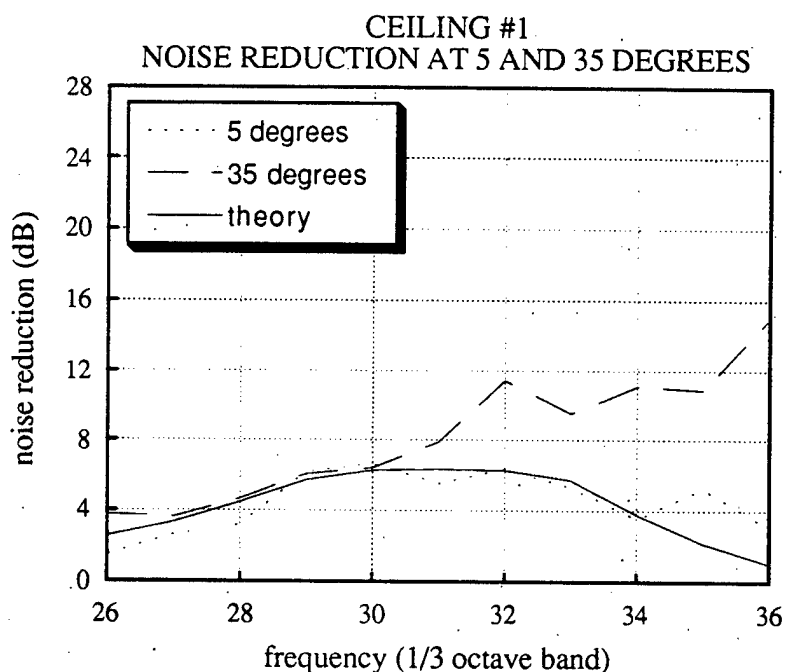


Figure 16. Transmission Loss at 5 and 35 Degrees for Ceiling #1.

A similar analysis can be applied to ceiling #2. Figure 17 shows the noise reduction at 5 and 35 degrees as dotted and dashed lines, respectively. Since the only change between ceiling #1 and ceiling #2 is the doubling of the ceiling depth, the theoretical

attenuation doubled over case #1. The appropriate theoretical curve is plotted as a solid line in Figure 17.

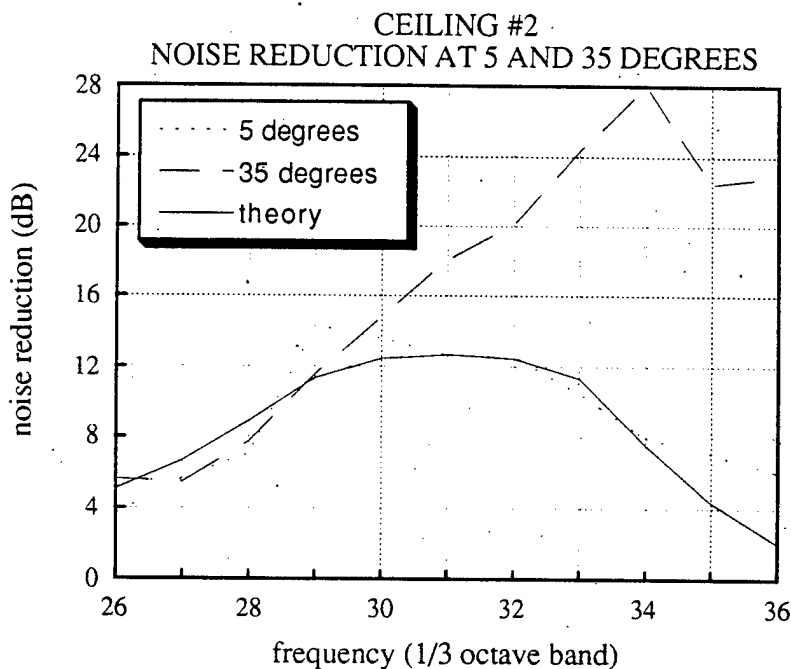


Figure 17. Transmission Loss at 5 and 35 Degrees for Ceiling #2.

As with ceiling #1, Cremer's theory accurately predicts noise reduction for data taken at a 5 degree angle of incidence with discrepancies found at 3.2 kHz and 4 kHz (band 35 and 36), presumably an effect of higher modes of propagation. An additional point of increased noise reduction is seen at 800 Hz (band 29). The reason for this is uncertain.

As with ceiling #1, measured noise reduction exceeds that predicted for data in which the angle of incidence is 35 degrees and the wavelength is larger than the duct width. The noise reduction increases rapidly for frequencies greater than 1 kHz due to a smaller presented area.

Ceiling #3, the staggered structure, does not exactly fit any theoretical curve. As discussed before, 5 and 35 degree angles of incidence are plotted in Figure 18. The same

theoretical curve used in Figure 17 is also plotted to show the change in noise reduction caused by staggering the ceiling.

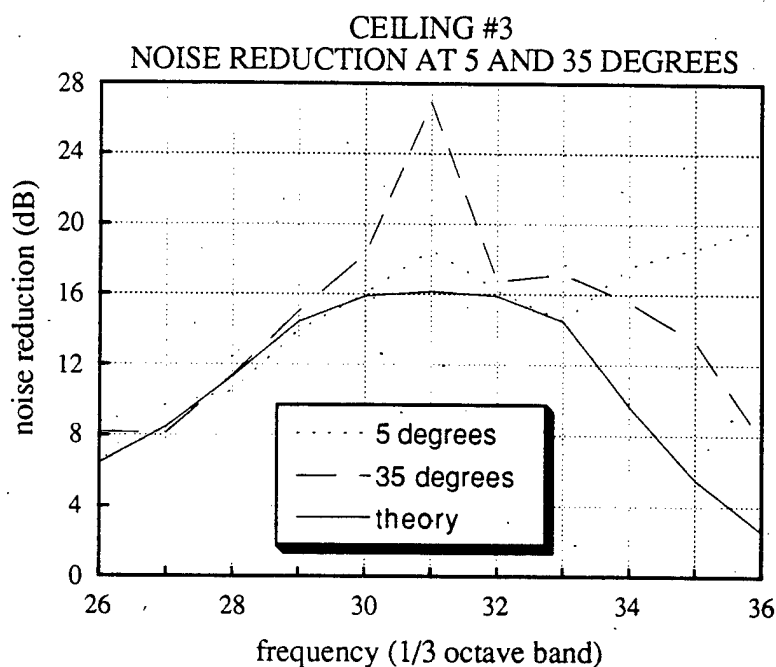


Figure 18. Transmission Loss at 5 and 35 Degrees for Ceiling #3.

For the 5 degree angle of incidence at low frequencies (band 26 and 27) and at 1250 Hz, noise reduction falls slightly above what the theory predicts. These deviations are slight compared to the trend observed at frequencies above 2 kHz (band 33). At these higher frequencies, the noise reduction data are shown to increase rather than decrease as the theory would suggest. The "tortuous" path that the wave must travel helps to attenuate more of the noise.

At 35 degrees, great noise reduction is measured at 1250 Hz. This may be due to a resonance produced by the partial blocking of the sound propagation. The upward trend of noise reduction at high frequencies that was apparent in ceilings #1 and #2 is not followed. The reason for this is unclear.

Figure 19 shows the relationship between curves at 5 degrees and 35 degrees. Upon decreasing the duct width for ceiling #4, the open area is decreased from 80 percent to $(4.5 \text{ in} / 6 \text{ in})^2 = 56$ percent. This corresponds to a curve between 50 and 67 percent. The weighted average of these curves is scaled and plotted in Figure 19.

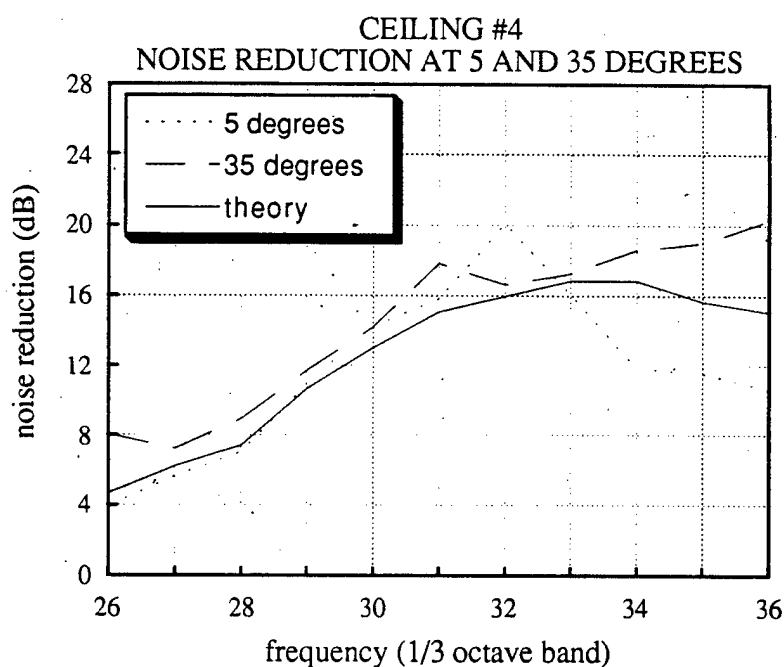


Figure 19. Transmission Loss at 5 and 35 Degrees for Ceiling #4.

For 5 degrees, low frequency noise reduction follows the theory as before. Increased noise reduction relative to theory is measured at 1.6 kHz, and decreased noise reduction is measured above 2 kHz.

For the 35 degree angle of incidence, noise reduction is 1 to 3 dB greater than theory would predict for frequencies up to 2.5 kHz. Above that frequency, the trend, evident in ceilings #1 and #2, of increased noise reduction for increased frequency is seen.

VI. FURTHER INVESTIGATION

A. Comparison to German Data

In order to further analyze the effectiveness of the ceilings tested at CERL, the measured data were compared to data taken from the range at Northeim, Germany. The German data were different because weighted sound exposure levels of gun fire were measured. In this study, intensities of continuous pink noise were measured. This is crucial when considering very low frequency differences since ground echo will taint the measurement of sound exposure levels.

As shown in Figure 2, measurements were taken along an arc around the shooter. Each point on the arc was 12.5 m from the shooter and above the line of fire. These measurements were made with and without the ceiling in stage 3 in place. In order to improve the statistics, 20 groups, consisting of 5 shots each, were fired. A German G-3 rifle was used. It is quite comparable to an American M-16.

The German data that most closely relate to the current study were gathered at position D (see Figure 2). The noise reduction measured at this location is shown as a solid line in Figure 20. Since our study was a scaled model, comparison between our data and the German data is made by scaling down our data from ceiling #1 at 35 degrees by five one-third octave bands. The CERL data are shown by a dashed line.

The deviations at 125 Hz and 156 Hz (band 21 and 22) may be attributed to ground echo. For the rest of the bands, CERL data are within 4 dB of the German data.

In Figure 21, the CERL data is also compared with German data taken in the far field (115 m behind the range). With the exception of 1.6 kHz (band 32), the German noise reduction data are higher, but they seem to form an upper bound to the CERL data. This indicates that using Cremer's design procedure would ensure that the desired noise reduction is achieved in the far field.

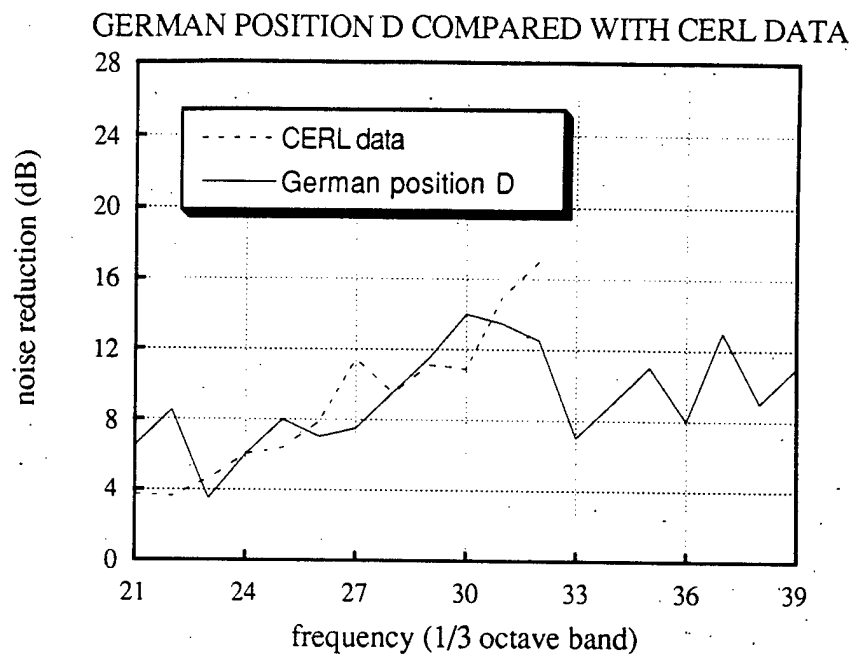


Figure 20. Noise Reduction Comparison above Buchta's Ceiling. Position D is 12.5 m above the ceiling 45 degrees behind the shooter.

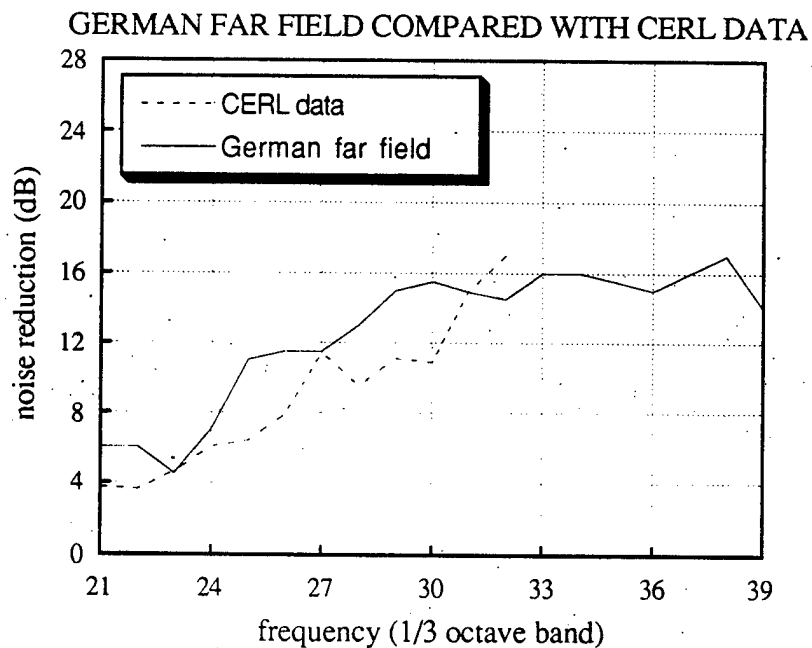


Figure 21. Noise Reduction Comparison in Far Field of Buchta's Ceiling.

B. Discussion of a Two-Stage Ceiling

As seen for ceilings #1, #2, and #4 at large angles of incidence, wavelengths smaller than the duct width are attenuated much more than the design curves predict. To attenuate high frequencies at small angles of incidence, a two-stage ceiling should be used directly above the noise source. The second stage should have a duct width substantially smaller than that of the first stage. Figure 22 shows the theoretical attenuation with a dotted line for a duct 4 ft wide and 8 ft deep. A dashed line indicates the attenuation for a duct 9.6 in wide and 19.2 in deep (one fifth the size of the previous duct). If two stages of ceilings were designed with these sizes of chambers, the overall attenuation of the system, ignoring impedance mismatch, at near normal incidence would be the sum of the two curves shown as a solid line. This provides a wider band of attenuation than a single stage would.

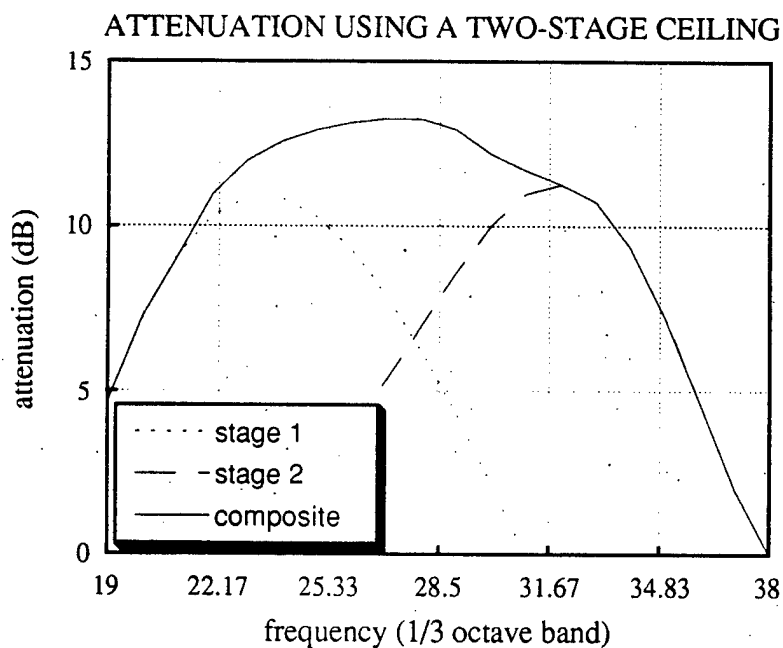


Figure 22. Two-Stage Ceiling.

If the two-stage structure were used directly above the noise source, attenuation of high frequencies would be maximized. Thus, the design of an effective ceiling depends on the use of a design curve for the first stage centered around the lowest frequency with substantial energy.

VII. CONCLUSIONS

The focus of this thesis is on an air-permeable ceiling which provides noise reduction especially at low frequencies. With Buchta's ceiling as a starting point, the effects of changing the depth and spacings within the ceiling were studied. Ceiling #1 is a one-third scaled model of Buchta's ceiling. From this ceiling we were able to match measured data to the results obtained by using Cremer's theory of attenuation in ducts. At large angles of incidence noise reduction increases with frequency. The CERL data at 35 degrees is scaled up and compared with German data at 45 degrees and in the far field. At 45 degrees, the data are within 4 dB of the CERL data, and in the far field, the data form an upper bound on the CERL data. Therefore, the scaled model study at CERL can be applied to noise reduction at an actual range.

From ceiling #2, the doubling of the depth is found to double noise reduction at all frequencies as theory would suggest. Frequencies that were not attenuated in ceiling #1 were not attenuated in ceiling #2.

To attenuate a different range of frequencies, the spacings between the baffles must change. In ceiling #4, the spacings are cut in half. This shifts the range of attenuated frequencies upward. As a side effect, overall attenuation is increased since the duct length is increased relative to the duct width. To attenuate lower frequencies, the depth of the chambers must be increased as well as the spacings between the baffles. As frequencies become lower, the required duct width (and depth) becomes very large. If the attenuation of lower frequencies is very important and size prevents the use of a large ceiling, alternative methods such as active filtering must be studied.

At higher frequencies and large angles of incidence, the staggered path in ceiling #3 does not provide as much attenuation as seen in ceiling #2. Therefore, it would not be an appropriate ceiling for a range except at smaller angles of incidence. Directly above the shooters, a ceiling #3 structure or a two-stage structure may be used to give added attenuation of high frequencies if needed.

According to the findings at CERL, if there continues to be a problem with low frequencies in communities near present rifle ranges, the depth of the baffles and the spacings between baffles will have to be increased. Directly above the firing locations a second stage may also be needed.

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